Improving Rural Internet Connectivity With Cellular Technologies

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1 INTRODUCTION

The Internet is playing an increasingly important role in education and creating new opportunities through offerings like OMSCS (Goodman, 2016).

As Internet speeds increase, new, previously impractical education opportunities open up. For example, Baratè (2019) reviewed how an existing online degree program was delivered using Internet connectivity options available to students in 2019. Baratè then examined how the performance and reliability improvements that 5G wireless technologies are expected to impact the program. The paper found that services that weren't viable to provide in 2019 would become viable with 5G.

The availability of these new opportunities is not uniform. One of the factors that makes these opportunities more available in densely populated areas is the cost of providing the last mile of service (Nandi, 2016).

In telecommunications, the most expensive part of providing service to customers is often the "last mile" or final leg of service delivery (Nandi, 2016). This is most true for fixed-line systems. For example, in telephony-based services, like DSL, the last mile is the infrastructure between the Central Office that serves an area, and each of its customers.

This last mile problem adds a new facet to the old problem of inequality of opportunity (Schütz, 2008).

Wireless telecommunications systems can mitigate the last mile problem. For example, in contemporary satellite-based telecommunications systems, the "last mile" is transmitting between the satellite and subscriber equipment, so the last mile cost is the cost of the subscriber's equipment. Because of this, the last mile cost in these systems does not differ significantly between urban and rural areas.

Cellular networks partially mitigate the last mile problem. They have the problem of needing to place cell towers at regular intervals to provide sufficient coverage,

which does increase the cost of serving rural areas. Still, that cost increase isn't as dramatic as it would be if a physical wire were run to each customer.

I created a website located at https://www.byobroadband.com/ to reduce the barriers to rural Internet users obtaining high-speed Internet access. The website does that by first introducing visitors to the idea that in some areas, technologies like 4G, LTE, and 5G can provide faster or cheaper Internet connectivity than traditional fixed-line Internet options, like cable and DSL. It then guides visitors through the process of deciding whether to switch to a cellular Internet connection and, if so, making the switch in four steps. Three example configurations are also provided, with different levels of speed, cost, and complexity.

2 RELATED WORK

Closing the gap between rural and urban Internet connectivity is an unsolved problem. The lack of a solution isn't due to a lack of attention or effort.

The Universal Service Fund has funded the expansion of telecommunications access since 1934 and Internet connectivity since 1997 (Rosston, 2000).

Satellite Internet access is widely available in rural areas, but so far, all available options have the downside of having high network latency. For example, typical round-trip network latency for a geosynchronous orbit satellite is 720ms (Cardaci, 2013).

SpaceX recently announced plans to make high-speed Internet available to most of the globe with a network of low-earth-orbit satellites orbiting at 500km. Starlink's website (n.d.) states:

> Starlink is targeting service in the Northern U.S. and Canada in 2020, rapidly expanding to near global coverage of the populated world by 2021.

Foust discussed the technical hurdles that SpaceX must overcome to accomplish its goal of using thousands of satellites to create Starlink (2019).

The Starlink network could improve access to high-speed Internet, but since the service doesn't exist yet, its impact is unknown.

Some MVNOs (mobile virtual network operators) have begun to cater to rural

Internet users. Examples include UbiFi (Unlimited 4G home Internet, 2020) and Simnet Wireless (Simnet Wireless, 2020).

LTE Hacks hosts message boards where discussions take place about obtaining Internet access through cellular networks (LTE Hacks, n.d.). Tutorials on how to accomplish specific tasks, like configuring routers for wireless Internet access, are also posted.

The Mobile Internet Resource Center is the closest thing that I could find to a single resource that ties everything together for cellular network Internet access in rural areas. It was an invaluable resource while creating BYOBroadband.com, and was referenced in a few areas. The Mobile Internet Resource Center's focus is on Internet access for recreational vehicle owners and boaters, though (Mobile Internet resource center, 2020), so it doesn't directly address rural residents who wish to improve their Internet access.

Private industry and government are each working to improve access to high-speed Internet, but so far, neither has come up with a silver bullet.

2.1 Why I selected this problem

The topic of rural Internet access is of direct interest to me. Eleven years ago, my wife and I moved from a small city where we had a fast (for the time) and reliable cable modem Internet connection to a rural area surrounded by National Forest. The only Internet connection options at our new home were a slow ADSL connection, high latency satellite, or dial-up.

When we moved here, the fastest available ADSL option ran at about 10Mbps down and 1Mbps up and was the clear winner in terms of affordable options. That's still the fastest affordable fixed-line Internet option.

The 10Mbps download speed was good enough for the most part, but only having around 1Mbps of upload capacity was a hindrance when video conferencing with coworkers or OMSCS students. I could see them clearly, but they saw a blurry, low-resolution version of me, due to the bandwidth constraints. Uploading large files was also painful at 1Mbps.

I ordered a second ADSL connection a few years ago and configured a router to load balance connections on a round-robin basis between the two ADSL lines. That helped, but each connection was still limited to 1Mbps uploads.

In early 2020, Jonathan (one of my coworkers), and I discussed SpaceX's plans to provide low latency satellite Internet via a service that they call Starlink (Foust, 2019). The service looked interesting. If it were available, reasonably priced, and as-advertised, then I'd sign up without hesitation. The service doesn't exist yet, though, so I don't know if it will work as advertised, how much it will cost, or even what year it will become available.

Jonathan had recently moved from Chicago to a rural part of Ohio and found that the best available Internet option for him was a cellular connection. He plugged an LTE router into an antenna mounted on his roof and pointed at the nearest cell phone tower. With that, he was able to get an Internet connection that ran at about 50Mbps down and 10Mbps up, compared to the next best option, which was an ADSL line advertised at 5Mbps down and 768Kbps up.

Jonathan was able to upgrade from what would have been a DSL connection even slower than mine to a one that was faster (5x as fast for downloads, and 10x as fast for uploads).

The conversation with Jonathan inspired me to do some research on whether a similar approach would work in my area. I reviewed the coverage maps of the cell phone carriers in this area, topological profiles between my house, and the nearest cell towers, what bands each provider used, and what equipment was on the market. While performing that research, I found that there were a lot of great resources on the Internet for specific topics, like how to pick an antenna or configure a router. Still, I couldn't find a guide tying everything together.

3 THE SOLUTION

BYOBroadband.com is a website created to improve rural Internet connectivity by educating visitors about cellular Internet options. It does that by first introducing visitors to the idea that in some areas, technologies like 4G LTE and 5G can provide faster or cheaper Internet connectivity than traditional fixed-line Internet options, like cable and DSL. It then guides visitors through the process of deciding whether to switch to a cellular Internet connection and if so, making the switch in four steps:

1. Check your coverage
2. Pick a mobile network and data plan
3. Select the right hardware

4. Install the hardware

3.1 Check your coverage

One of the things that a potential cellular Internet user needs to do is determine which networks provide coverage in their area, and how good the coverage is. While the most reliable way to find out is to get a compatible device, and test coverage, there are less expensive options as well. The "Check your coverage" step at https://www.byobroadband.com/check-coverage/ covers:

1. An introduction to the US's four major cellular networks and their resellers
2. Official coverage maps
3. What key terms like 4G, LTE, and 5G mean
4. Speed requirements
5. Costs
6. How to check signal strength using an Android or iOS smartphone
7. How to run speed tests

3.2 Pick a mobile network and data plan

There may only be a few major network operators in the US, but each of them has numerous offerings and MVNOs (mobile virtual network operators) with their own offerings. The "Pick a mobile network and data plan" step at https://www.byobroadband.com/pick-mobile-network-and-data-plan/ helps the reader to navigate their options by covering the following:

1. Key terminology
2. Estimating data usage and bandwidth requirements
3. Deciding whether to tether to a smartphone or use a dedicated device
4. A comparison of smartphone plans that allow tethering
5. A comparison of dedicated device plans that can be used by hotspots and routers

3.3 Select the right hardware

Readers who want to move forward have many hardware options available. The "Select the right hardware" step at https://www.byobroadband.com/select-hardware/, breaks the hardware selection process down into the following sub-steps:

1. Pick a radio (such as a cell phone, hotspot, or router)
2. Pick an antenna configuration

3. Consider an amplifier
4. Consider lightning protection
5. Add cabling

3.4 Install the hardware

After the hardware's selected, it still needs to be installed. The installation step at https://www.byobroadband.com/install-hardware/ covers the following topics:

1. Deciding whether to do it yourself or hire a professional
2. Picking an antenna location
3. Antenna polarity, aiming and mounting
4. Lightning protection
5. Cabling
6. Waterproofing
7. Testing
8. Troubleshooting tips

3.5 Example configurations

The website's example configurations section shows three configurations at https://www.byobroadband.com/lte-examples/. The documentation for each includes:

1. A discussion of how I used the website's four-step process to set up the Internet connection
2. Performance characteristics
3. Problems that were overcome
4. Costs

4 METHODOLOGY

The website was evaluated and refined using the following techniques:

1. Three direct evaluations were performed by applying the website's four-step process while setting up actual Internet connections.
2. Feedback was solicited from students in the course that this paper was written for (CS 6460: Education Technology) in two surveys, and two intermediate milestone videos.

4.1 Direct evaluations

The website's four-step process for setting up cellular Internet connectivity was applied to set up three Internet connections in a rural area:

1. An outdoor installation that uses two external antennas
2. Tethering to a cell phone
3. An indoor installation using a hotspot and an antenna

4.2 Surveys

Two, 10-question surveys were conducted using Georgia Tech's PeerSurvey website, located at http://peersurvey.cc.gatech.edu/. Each survey received 25 responses. The questions that were in each survey are in this document's appendices.

4.3 Peer feedback from intermediate milestone videos

Two intermediate milestone videos were recorded:

1. Intermediate milestone video 1
2. Intermediate milestone video 2

Classmates provided feedback using Georgia Tech's Peer Feedback website, located at https://peerfeedback.gatech.edu/. Seven classmates provided feedback on the first video, and six provided feedback on the second video.

5 THE RESULTS

Here are the results of each evaluation:

5.1 Direct evaluations

The three direct evaluations are documented at https://www.byobroadband.com/lte-examples/, so this section contains only a brief summary of each.

5.2 Evaluation 1: An outdoor installation that uses two external antennas

The first direct evaluation was performed using an installation that includes two outdoor antennas. It currently serves as my primary Internet connection and is documented at https://www.byobroadband.com/lte-examples/outdoor-installation/.

This installation has the fastest uploads of the three configurations but was also

the most expensive and labor-intensive to setup. Similar configurations are suitable for those who live in areas that are so remote that an indoor installation doesn't provide enough performance.

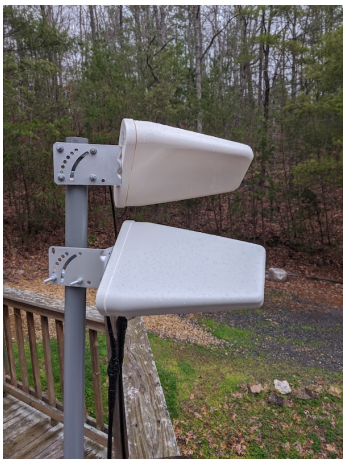

Figure 1—Two outdoor, cross-polarized 4G LTE antennas connected to AT&T's network.

Because of the complexity of this installation, it was done in phases, starting with a prototype, which was intended to be the minimal potentially viable configuration. Here's the assembled prototype:

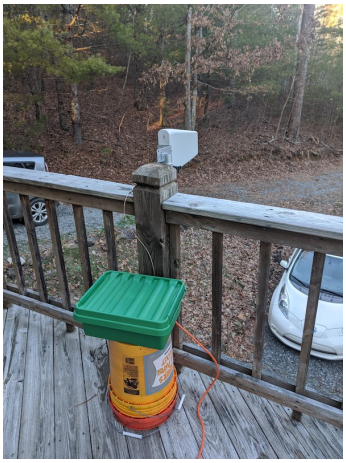

Figure 2—A working prototype for rural Internet access.

The prototype worked better than I expected. The connection had about 1.2x the download speed of my DSL connection, which was nice, but the more significant upgrade was that the upload speed was 12x as fast as what DSL provided.

After the prototype went into operation, it was incrementally upgraded until it reached its final configuration. In terms of performance and reliability, here's what changed since the prototype first went into operation:

1. Intermittent connectivity issues were resolved
2. The connection speed changed from 12Mbps/12Mbps with occasional dips to under 1Mbps/1Mbps to a stable 20Mbps/12Mbps +/- 10%
3. The router is now indoors, with lightning protection and battery backup

I work and attend OMSCS classes from home. Anecdotally, the boost in Internet connection speed that this upgrade has provided is a significant improvement for both work and school. Even areas where I thought my old connection was "good enough", such as performing research, are perceptibly faster.

5.3 Evaluation 2: tethering to a cell phone

The second direct evaluation was performed by tethering an Android smartphone (a Pixel 3a with a Google Fi subscription) to a GL.iNet GL-AR750 router and access point. It's documented at https://www.byobroadband.com/lte-examples/tethering-to-cellphone/:

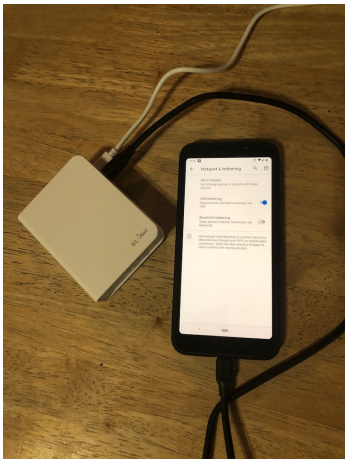

Figure 3—A Pixel 3a smartphone tethered to a GL.iNet GL-AR750.

This is the simplest of the three systems. It took about an hour and $52.99 worth of equipment to set up. It's ideal for short-term or backup configurations. This is currently my backup Internet connection.

The reason for the router's inclusion in this configuration is to allow the cell phone to be placed in the spot that gets the best cellular signal but still provide

WiFi coverage throughout the house. The cell phone's built-in WiFi transceiver doesn't have enough range to do that.

5.4 Evaluation 3: An indoor installation

The final direct evaluation was performed using a MiFi 8000 hotspot and a Netgear 6000450 MIMO antenna. It's documented at https://www.byobroadband.com/lte-examples/indoor-installation/:

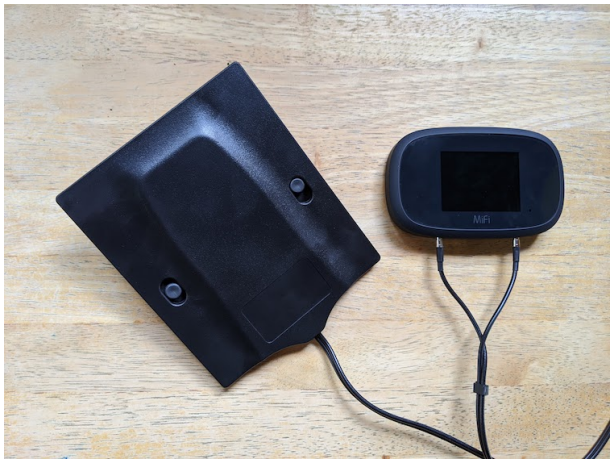

Figure 4—A MiFI 8000 hotspot and Netgear antenna connected to Sprint's network.

I don't currently use this installation. It was set up temporarily for this project, to provide an example configuration that's easier and cheaper to set up than the outdoor antenna installation, but faster than the cell phone tethering installation.

5.5 Surveys

The following themes emerged in survey responses:

1. The site looks like it will be beneficial to rural residents
2. Increase emphasis on the performance and cost benefits
3. Add more photos and figures to make the site easier to digest
4. Break up long pages to make them easier to digest

5.6 Peer feedback from intermediate milestone videos

The feedback received on intermediate milestone videos was very similar to what was received in the surveys. The comments that were unique to the video feedback tended to be about the videos themselves.

6 CONCLUSION

The performance and price gaps between rural and urban Internet access is an ongoing problem, for which there's not likely to be a silver bullet. One option for narrowing the gaps is for rural residents to consider cellular Internet connectivity options. In some cases, they'll find that their cellular Internet connection options are faster or less expensive than traditional fixed-line options, like DSL and cable. The BYOBroadband.com website guides rural Internet users through that process.

7 LIMITATIONS AND FUTURE WORK

The website targets rural readers within the United States who wish to improve Internet connectivity at a fixed location. As a result, other types of readers, like those who live in other areas, will find that the website's content doesn't map as well to their requirements. This was a useful constraint for limiting project scope. Broadening the website's target audience is a potential area of future work.

As the "Surveys" section shows, a recurring suggestion made by peers was to "Break up long pages to make them easier to digest". I've started on this work.

The list of mobile carriers in the US will change as the 2020 merger between T-Mobile and Sprint is implemented (T-Mobile and Sprint merger FAQs, 2020). As of the time this paper was written, the two networks are still separate. The website will be updated as T-Mobile and Sprint's networks merge, and Dish emerges as a new option.

Parts of the website are expected to become out of date in the next few years unless they're updated. For example, as 5G technologies become common, I anticipate they'll receive more coverage on the website. Urban areas are the first to benefit from 5G, but it's reasonable to expect that, like 4G and LTE before it, 5G becomes prevalent in rural areas as well. 5G networks fall into three categories (Morgado, 2018):

1. Low-band - below 1GHz. This is the longest range, but slowest of the three categories.
2. Mid-band - 1GHz-6GHz - the midway point between low-band and millimeter. This frequency range overlaps with the range that most 4G LTE devices use.
3. High-band - above 6GHz. Also known as millimeter wave. This is the vari-

ant that's capable of the fastest transmission, but it's also the most limited in range.

High-band is appealing from a raw performance perspective. Still, realistically, the poor propagation of such high-frequency radio frequencies means that its unlikely to find its way into most rural areas (Aziz, 2016). Since mid-band's frequencies overlap with 4G LTE's, it is expected to have similar propagation characteristics (Morgado, 2018). Low-band 5G may turn out to be a compelling option for rural Internet users. It could expand cellular coverage to areas that currently lack coverage.

Another area of potential work is low earth orbit satellite networks. For example, SpaceX's Starlink network, which is expected to become operational later in 2020, could become a competitive option for some rural Internet users (Foust, 2019).

8 REFERENCES

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9 APPENDICES

9.1 Survey 1

Here are the questions that were asked in survey 1:

1. Select your age
2. What best describes the type of area you live in?
3. What is your primary Internet connection at home?
4. What are the approximate download and upload speeds provided by your home Internet connection? If you're not sure, you can visit https://www.speedtest.net/ to find out.
5. Which of the following best describes how you feel about your home Internet connection speed?
6. If you wish your Internet connection was faster, which of the following metrics would you most like to improve?
7. Which of the following best describes what upgrading to a faster home In-

ternet connection would be like for you? Think of "technical barriers" in the context of the average person, rather than what you personally would find challenging.

8. If your answer to the previous question indicated that there are technical barriers, please describe them.
9. Please visit https://www.byobroadband.com/ and review the home page. Do you have any comments or recommendations for improvement?
10. Please visit https://www.byobroadband.com/case-study/ and review the page. It's a long page, so it's okay to scan. Do you have any comments for recommendations for improvement?

9.2 Survey 2

Here are the questions that were asked in survey 2:

1. Select your age
2. What best describes the type of area you live in?
3. What is your primary Internet connection at home?
4. What are the approximate download and upload speeds provided by your home Internet connection? If you're not sure, you can visit https://www.speedtest.net/ to find out.
5. Which of the following best describes how you feel about your home Internet connection speed?
6. If you wish your Internet connection was faster, which of the following metrics would you most like to improve?
7. Please visit https://www.byobroadband.com/ and review the home page. Is the purpose of the site clear to you? Do you have any ideas for making the site's purpose more clear?
8. Please visit https://www.byobroadband.com/case-studies/ and briefly review the three case studies. Do you have any comments or recommendations?
9. Please visit https://www.byobroadband.com/, and briefly review the four-step process that it outlines for setting up cellular Internet access (it's numbered 1-4). Do you have any comments or recommendations?
10. Do you have any other comments or suggestions?